PHYTOPLANKTON AND MICROCYSTIN-LR IN THE ASSINIBOINE RIVER AT PORTAGE LA PRAIRIE, MANITOBA, 1997 - 2001

By Geoff Jones

Water Quality Management Section,
Water Branch

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INTRODUCTION

Blue-green algae (also known as cyanobacteria, cyanophyta, or myxophyceae) are a group of single-celled organism that have characteristics in common with both bacteria and algae. For example, like bacteria they a lack a definite nuclear membrane, while, like algae, they contain chlorophyll and are capable of photosynthesis. A number of species of blue-green algae are able to produce toxins that attack the liver (hepatotoxins) and nervous system (neurotoxins). A potent, but difficult to detect type of neurotoxin is anatoxin, which is produced by freshwater species of *Anabaena*, *Aphanizomenon*, and *Oscillatoria* (Carmichael 1994b). Neurotoxins cause muscle twitching and cramping followed by fatigue, paralysis, and often death (Carmichael 1994a). Hepatotoxins, in sufficient concentrations, can cause extensive necrosis of the liver, which can lead to liver failure and death after a few hours to a few days. Microcystin-LR is considered the most common hepatotoxin in the prairie provinces (Kotak 1995). Microcystin-LR inhibits the enzymatic activity of phosphatases 1 and 2A (Sahin *et al.* 1995). Phosphatases 1 and 2A are responsible for the removal of phosphate groups from protein molecules, and as such, are very important in regulating cellular function, particularly microfilament development (Sahin *et al.* 1995). Sub-lethal ingestion of blue-green algae hepatotoxins have also been implicated as a tumor promoter (Falconer 1991, Nishiwaki-Matsushima *et al.* 1992). Some genera that have been identified as producers of liver toxins include: *Microcystis*, *Nodularia*, *Oscillatoria*, *Anabaena*, and *Aphanizomenon* (Harada *et al.* 1991, Sivonen *et al.* 1992, Carmichael 1994b).

Livestock, wildlife, and pet poisonings from consumption of blue-green algae toxins have been reported for the last 100 years. In Canada, algal toxins have been isolated from water supplies in the western provinces (*e.g.*, Carmichael and Gorham 1978; Kotak *et al.* 1993). Animal deaths from algae ingestion in Manitoba were reported as early as 1951 (McLeod and Bondar 1952). In this instance, a horse and nine dogs died after ingesting water from Dauphin Lake.

It is difficult to predict the development of blue-green algae blooms and toxin production. Although several studies have been undertaken to determine the relationship between toxin concentrations and environmental variables (see Kotak 1995), there has been no consensus on which environmental variables are most influential. Studies by Wicks and Theil (1990), Kotak (1995), Kotak *et al.* (1995), and Jones *et al.* (1998) found that phosphorus and nitrogen concentration, and the temperature of the water, were positively correlated with microcystin-LR concentration. Yoo *et al.* (1995) suggested that no single variable can be used as an indicator of blue-green algae growth and subsequent toxin production, but rather a whole host of

environmental factors such as high nutrient content, low nitrogen to phosphorus ratios, warm water temperatures, and a high pH, work in concert to promote growth and toxin production.

Phosphorus is released into surface water through weathering of soil and rock and the decomposition of organic material. Domestic and industrial sewage, as well as run-off from fertilized cultivated lands and livestock areas, also contributes significantly to the total phosphorus (TP) in surface waters (CCME 1987). According to Williamson (1988), concentrations of TP above 0.025 mg/L in lakes, ponds, and reservoirs, and greater than 0.05 mg/L in rivers and streams increases the risk for excessive algae growth to take place. This will also depend on the water clarity and concentration of other nutrients in the water, particularly the amount of nitrogen. Nitrogen enters the aquatic environment through gas exchange with the atmosphere, the decomposition of plant material and animal wastes, and as leachate from igneous rocks (CCME 1987). Nitrogenous compounds such as nitrates and ammonia are also principle ingredients in many soil fertilizers. Thus, in agricultural regions the run-off from fertilized cropland can be a significant source of nitrogen for surface water supplies.

Manitoba Conservation has been monitoring selected surface waters in the province for the presence of microcystin-LR since 1993. The results of a rural water quality survey conducted in southern Manitoba in 1995 revealed that microcystin-LR was present (detection limit of 0.1 µg/L) in 70% of the 158 raw water supplies sampled (Jones *et al.* 1998). This included 93% or 28 of 30 municipal drinking water supplies included in the survey. The toxin was also found to be present in 68% of the treated water samples submitted from these municipal sites, thus indicating that conventional treatment methods were only partially successful in toxin removal. More detailed periodic sampling at a small number of sites (including three municipal drinking water supplies) in 1996, indicated that microcystin-LR could be present in raw water supplies from June through to December (Jones *et al.* 1998). The 1996 results also showed that some water treatment facilities were not capable of removing significant amount of toxins from the raw water. Statistical analysis of the detailed data collected in 1996 showed that there was no clear relationship between toxin concentrations and blue-green algal densities, nor was there any correlation between toxin concentrations and environmental variables. Thus, the production and concentration of microcystin-LR in a water body was found to be difficult to predict based on water chemistry and phytoplankton composition.

In 1997 the microcystin-LR monitoring program was expanded to include a total of 17 municipal water supplies. Monitoring was conducted for two consecutive growing seasons. All of the sites sampled had detectable levels of the toxin in their raw water supply at some time during the monitoring program (Jones 1999). Concentrations varied considerably both between

sites and between years. In general, the highest concentrations of the toxins at the sites occurred in samples collected during the month of August and the period from October to November. Treated water samples submitted for analysis had toxin concentrations as high as 1.0 µg/L.

A Canadian drinking water quality guideline is under development to protect the public from the health risks associated with acute and chronic exposure to microcystin-LR. Although not formally finalized, a guideline of 1.5 µg/L in finished drinking water has been proposed (Health Canada 2001). None of the municipal treated water samples collected during the 1997 and 1998 growing seasons exceeded this proposed guideline level (Jones 1999). In fact, the vast majority of the treated water samples tested had concentrations less than 0.5 µg/L, and many of these were reported as below detection.

The Portage la Prairie water treatment plant (WTP) was one of the participants in the municipal drinking water survey conducted in 1997 and 1998. Manitoba Conservation, with the co-operation of the City of Portage la Prairie, continued a regular monitoring program of the city's water supply from 1998 until the end of 2001. The main objective of this program was to obtain long-term data of toxin concentrations and phytoplankton community structure in a multi-use surface water supply. This report will present the findings of this monitoring program.

STUDY SITE LOCATION AND SAMPLE COLLECTION

The Assiniboine River originates in southeastern Saskatchewan near the community of Preeceville in southeastern Sasktchewan (Figure 1). The river meanders in a southeast direction from its headwaters into Manitoba and then eastward to eventually empty into the Red River at Winnipeg. Several streams flow into the Assiniboine along its course including the Qu'Appelle River and the Souris River, both of which originate in Saskatchewan, and smaller tributaries such as the Little Saskatchewan River and the Cypress River.

Approximately 60% of the relatively large (41500 km^2) Assiniboine River watershed is located within the boundaries of Manitoba. Agricultural activity within the watershed is very intense (Upper Assiniboine River Basin Study Committee 2000) and ranges from cereal, feed, and specialty crop production, to range and pasture lands, to cattle feedlot and large hog barn operations. The river is a source of water for industrial and recreational use, agriculture crop irrigation, and domestic and livestock consumption. The river also receives treated effluent from a number of municipal and industrial wastewater treatment facilities, such as those at the cities of Brandon and Portage La Prairie, and Maple Leaf Foods (east of Brandon).

The city of Portage la Prairie is located on the north side of the Assiniboine River about 75 km (straight line distance) west of Winnipeg (Figure 1). A flood control structure (dam, spillway, and diversion channel) was built on the river at Portage la Prairie in 1970 to divert river water northward to Lake Manitoba during periods of high water flow in the river. The construction of the dam and spillway created a reservoir on the river that is the present source of raw water for the community. The city's WTP is located adjacent to the north bank of the river immediately downstream of the dam and spillway. Raw water is piped from the reservoir to the WTP via a pumping station located at the dam. The water passes through a relatively complex treatment chain within the WTP that includes contact with potassium permanganate, softening and clarification, recarbonation, ozonation, sand filtration, chlorination, and fluoridation prior to distribution (City of Portage la Prairie 1999). The city is presently (2002) up-grading the WTP to increase its overall treatment capacity and to incorporate the removal of colour, turbidity, algae, organic material, parasitic organisms, and disinfection by-products in the treatment chain.

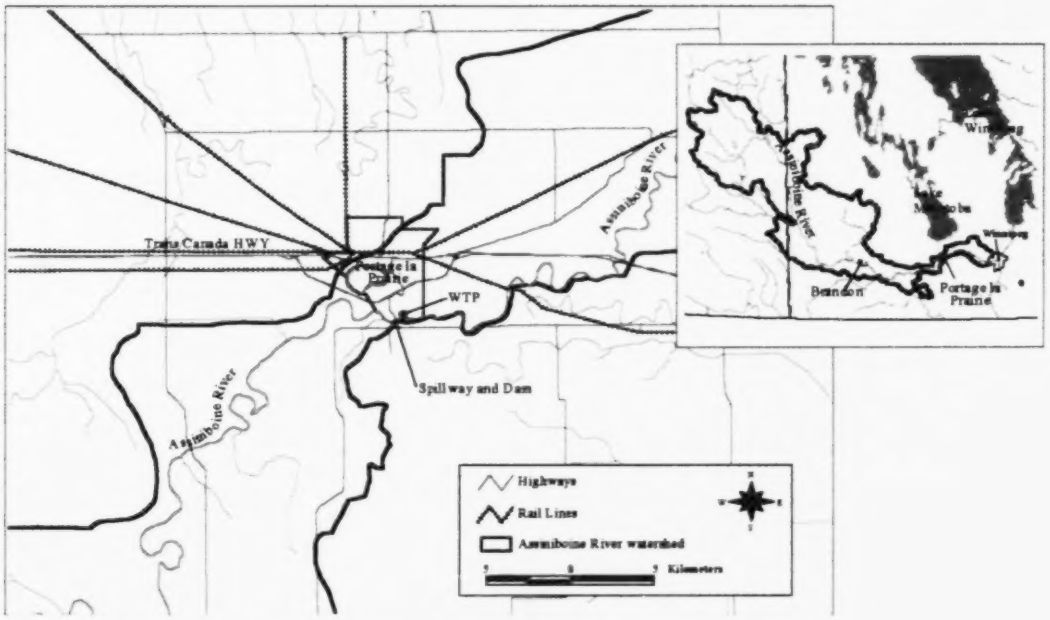

Figure 1. Map showing the location of the spillway, dam, and water treatment plant on the Assiniboine River at Portage La Prairie, MB.

The nutrient status of the Assiniboine River immediately downstream of the spillway and dam has been monitored at regular intervals for over 30 years. During this period, TN and TP concentrations in the river have fluctuated mainly between 0.5 to 1.5 mg/L and 0.1 to 0.2 mg/L, respectively. Statistical analysis of the long-term trends in flow-adjusted nutrient concentrations indicate that from 1973 to 1999 median TN concentrations at this point in the river increased by 20.5%, while median TP concentrations increased by almost 40% (Jones and Armstrong 2001).

Regular monitoring for microcystin-LR in the Assiniboine River at the WTP in Portage la Prairie began in the spring of 1997 and concluded in December 2001. The program involved collecting raw water samples from the raw water tap located in the pump house at the dam/spillway structure and treated water samples from the treated water tap in the WTP. Samples were collected at monthly intervals in 1997, while in 1998 through 2001 samples were collected at weekly to biweekly intervals during the growing season (April – October) and at roughly monthly intervals during the winter (November – March). At each sampling date, a single raw water sample (125 mL) and a single treated water sample (125 mL) were collected for microcystin-LR and phytoplankton identification (raw water only). As well, beginning in May 1999, a 1000 ml raw water sample was collected for chlorophyll-*a* analysis.

Samples for toxin analysis were kept cool until submitted to the Protein Phosphatase Bioassay Laboratory (Dr. Charles Holmes), University of Alberta, Edmonton, AB. Quantification of microcystin-LR was done using the protein phosphatase bioassay as described in Lambert *et al.* (1994). All raw water samples were analyzed for the toxin. A treated water sample was considered for analysis only if the corresponding raw water sample had registered positive for the toxin. In addition to the laboratory quality assurance/quality control measures, blind blanks and replicate samples were periodically collected and analyzed for microcustin-LR during the course of monitoring. Chlorophyll-*a* was extracted with acetone and analyzed using a spectrophotometer. Phytoplankton identification and estimations of density and bio-volume were performed using a high power inverted light microscope.

RESULTS

Microcystin-LR

The microcystin-LR data are presented graphically in Figure 2, while the complete data set is available in the Appendix. One hundred thirteen raw water samples and nine treated water samples were tested for microcystin-LR. The majority (67%) of the raw water samples collected over the period of monitoring had levels of microcystin-LR below detection (Figure 2).

Microcystin-LR concentrations varied considerably over the course of the study. However, in general, the highest concentrations occurred during the summer and fall months of each year. The highest toxin concentration recorded during the survey was 0.7 µg/L in a raw water sample collected in August 1998. This level was still well below the proposed drinking water guideline of 1.5 µg/L. The toxin was not detected in the corresponding treated water sample for this date or the subsequent two sample dates. If fact, the toxin was not detected in any of the nine treated water samples analyzed over the course of the program, even though it had been detected in the corresponding raw water samples.

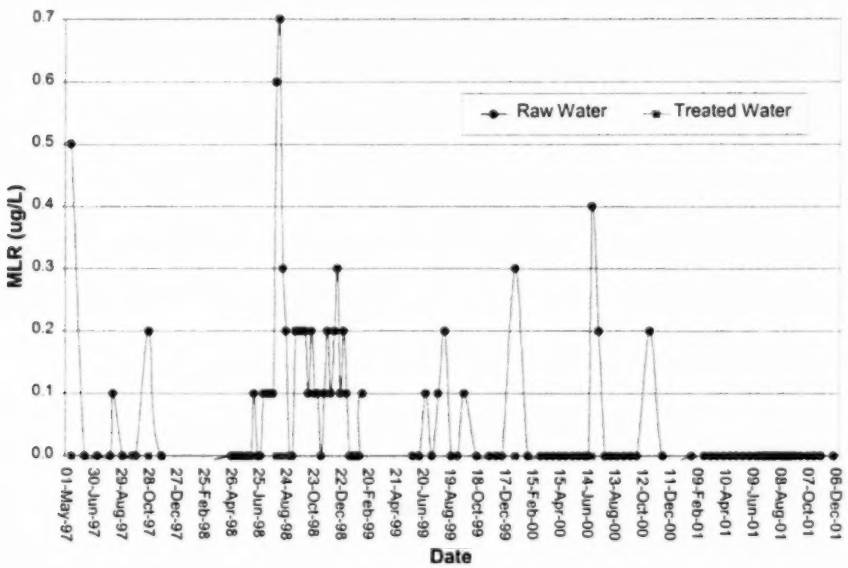

Figure 2. Microcystin-LR (MLR) concentrations in raw and treated water samples collected at the Portage la Prairie WTP from May 1997 to December 2001. Note that zero values on the graph actually represent values < detection. Detection limits were <0.1 µg/L from May 1997 – April 2000 and <0.2 µg/L from May 2000 – December 2001.

Chlorophyll-*a*

Chlorophyll-*a* concentration is an indicator of the amount of phytoplanton (planktonic or free-floating algae) present in a water sample. Fifty-nine raw water samples were collected and analyzed for chlorophyll-*a* concentration from June 1999 to December 2001. Concentrations of chlorophyll-*a* ranged from <1 µg/L in late March 2001 to 110 µg/L in October 1999 (Figure 3). The majority (58%) of the samples had concentrations below 10 µg/L. Peaks in concentration were sporadic and occurred in the fall of 1999, the spring and late summer of 2000, and the spring, mid-summer, and early winter of 2001.

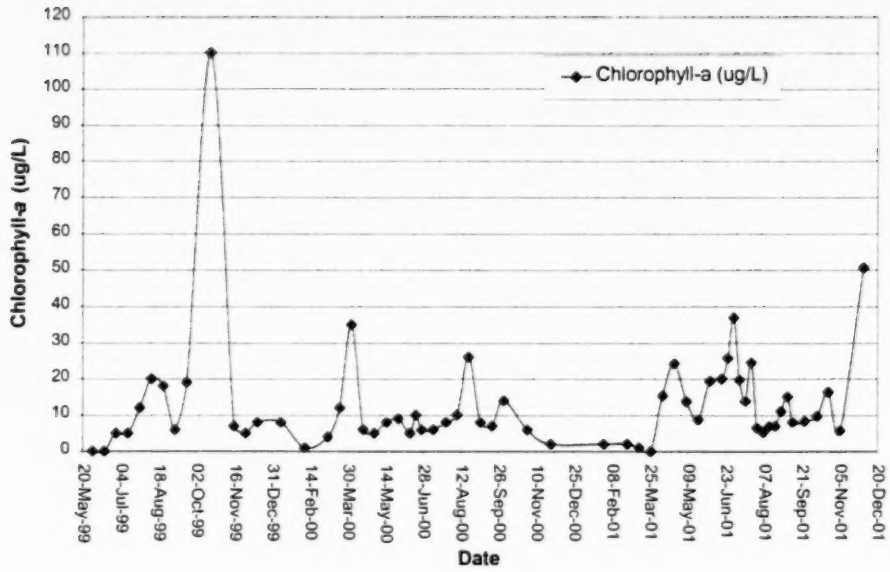

Figure 3. Chlorophyll-*a* concentrations in raw water samples collected from the Assiniboine River at the Portage la Prairie WTP from May 1999 to December 2001.

Phytoplankton

Algal identification and estimates of cell density and bio-volume were carried out on 56 raw water samples collected from June 1999 through to December 2001. Eighty five species of phytoplankton representing seven major classes or groups of algae were found in the raw water samples tested (Table 1). The diatoms (Class Bacillariophyceae) were the overwhelmingly dominant algal group in terms of density and bio-volume measurements (Figures 4 and 5, respectively). The Chlorophyceae or green algae, although represented by more species than the Bacillariophyceae (see Table 1), were a distant second in terms of population size.

The blue-green algae (Class Myxophyaceae) were well represented with at least 17 species identified over the course of the monitoring program. The most common blue-green algae were *Aphanizomenon flos-aquae* and species of *Lyngbya*, *Merismopedia*, and *Anabaena*. Peaks in blue-green algae populations were observed during the late-summer and fall of 1999 and the fall of 2000. These peaks were, however, relatively minor and generally, the blue-green algae did not constitute a very large portion of the overall phytoplankton population (Figure 6).

A table summarizing the density and bio-volume data for each phytoplankton class, along with the complete data set for blue-green algae species are available in the Appendix section.

Table 1. Phytoplankton collected from the Assiniboine River at the Portage la Prairie WTP from June 1999 to December 2001.

Class	Species	Class	Species
Bacillariophyceae	*Achnanthes minutissima*	Chlorophyceae	*Actinastrum hantzschii*
Bacillariophyceae	*Asterionella formosa*	Chlorophyceae	*Actinastrum* sp.
Bacillariophyceae	*Cocconeis placentula*	Chlorophyceae	*Botryococcus braunii*
Bacillariophyceae	*Cocconeis* sp.	Chlorophyceae	*Carteria* sp.
Bacillariophyceae	*Cyclotella* sp.	Chlorophyceae	*Chlamydomonas* sp.
Bacillariophyceae	*Cymbella* sp.	Chlorophyceae	*Closterium setacem*
Bacillariophyceae	*Diatoma* sp.	Chlorophyceae	*Closterium setaceum* f.sigmoideum
Bacillariophyceae	*Epithemia* sp.	Chlorophyceae	*Closterium* sp.
Bacillariophyceae	*Fragilaria crotonensis*	Chlorophyceae	*Coelastrum micorporum*
Bacillariophyceae	*Fragilaria* sp.	Chlorophyceae	*Coelastrum* sp.
Bacillariophyceae	*Gomphonema* sp.	Chlorophyceae	*Cosmarium* sp.
Bacillariophyceae	*Melosira* sp.	Chlorophyceae	*Crucigenia quadrata*
Bacillariophyceae	*Navicula* sp.	Chlorophyceae	*Crucigenia* sp.
Bacillariophyceae	*Neidium* sp.	Chlorophyceae	*Dictyosphaerium pulchellum*
Bacillariophyceae	*Nitzschia* sp.	Chlorophyceae	*Dictyosphaerium* sp.
Bacillariophyceae	*Pinnularia* sp.	Chlorophyceae	*Kirchneriella* sp.
Bacillariophyceae	*Pleurosigma* sp.	Chlorophyceae	*Monoraphidium* sp.
Bacillariophyceae	*Rhoicosphenia* sp.	Chlorophyceae	*Oocystis* sp.
Bacillariophyceae	*Stephanodiscus niagarae*	Chlorophyceae	*Pediastrum boryanum*
Bacillariophyceae	*Stephanodiscus* sp.	Chlorophyceae	*Pediastrum duplex*
Bacillariophyceae	*Surirella* sp.	Chlorophyceae	*Pediastrum simplex*
Bacillariophyceae	*Synedra acus*	Chlorophyceae	*Scenedesmus acuminatus*
Bacillariophyceae	*Synedra ulna*	Chlorophyceae	*Scenedesmus arcuatus*
Bacillariophyceae	*Synedra* sp.	Chlorophyceae	*Scenedesmus armatus*
Bacillariophyceae	*Tabellaria* sp.	Chlorophyceae	*Scenedesmus bijuga*
		Chlorophyceae	*Scenedesmus dimorphus*
Myxophyceae	*Anabaena* sp.	Chlorophyceae	*Scenedesmus quadricauda*
Myxophyceae	*Aphanizomenon flos-aquae*	Chlorophyceae	*Schroederia judayi*
Myxophyceae	*Aphanocapsa delicatissima*	Chlorophyceae	*Sphaerocystis schroeteri*
Myxophyceae	*Aphanocapsa* sp.	Chlorophyceae	*Staurastrum* sp.
Myxophyceae	*Chroococcus* sp.	Chlorophyceae	*Tetraedron* sp.
Myxophyceae	*Coelosphaerium* sp.	Chlorophyceae	*Ulothrix* sp.
Myxophyceae	*Gomphosphaeria* sp.		
Myxophyceae	*Lyngbya limnetica*	Cryptophyceae	*Cryptomonas* sp.
Myxophyceae	*Lyngbya* sp.	Cryptophyceae	*Rhodomonas minuta*
Myxophyceae	*Merismopedia punctata*	Cryptophyceae	*Rhodomonas* sp.
Myxophyceae	*Merismopedia tenuissima*		
Myxophyceae	*Merismopedia* sp.		
Myxophyceae	*Microcystis aeruginosa*	Euglenophyceae	*Euglena* sp.
Myxophyceae	*Microcystis* sp.	Euglenophyceae	*Phacus* sp.
Myxophyceae	*Planktolyngbya* sp.	Euglenophyceae	*Trachelomonas* sp.
Myxophyceae	*Pseudoanabaena* sp.		
Myxophyceae	*Spirulina* sp.		
		Peridineae	*Glenodinium* sp.
Chrysophyceae	*Dinobryon* sp.	Peridineae	*Gymnodinium* sp.
Chrysophyceae	*Mallomas* sp.	Peridineae	*Peridinium* sp.

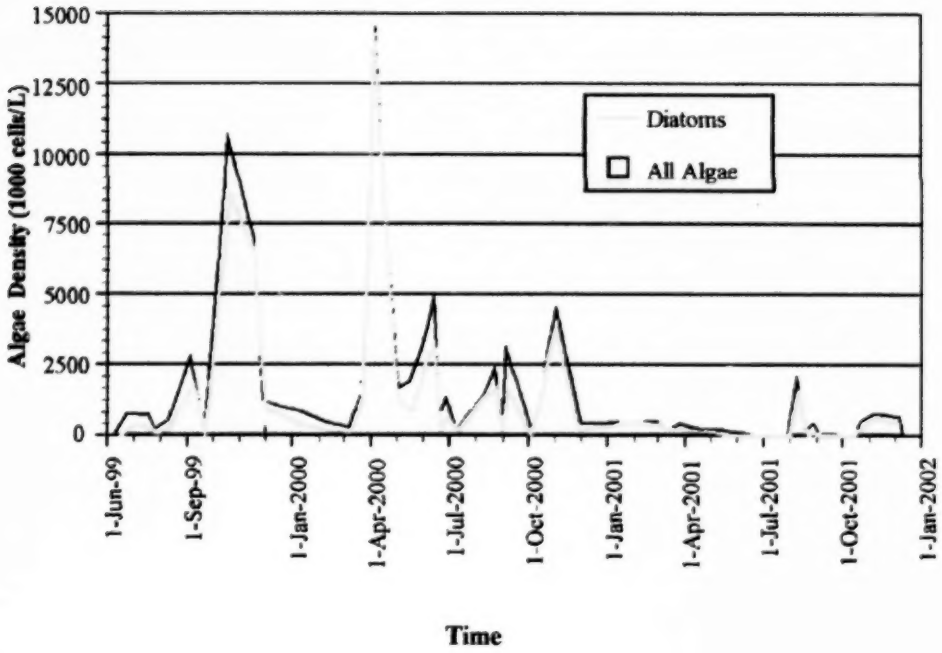

Figure 4. Comparison between the total algal density and the density of diatoms (Class Bacillariophyceae) in samples collected from the Assiniboine River at the Portage la Prairie WTP from June1999 to December 2001.

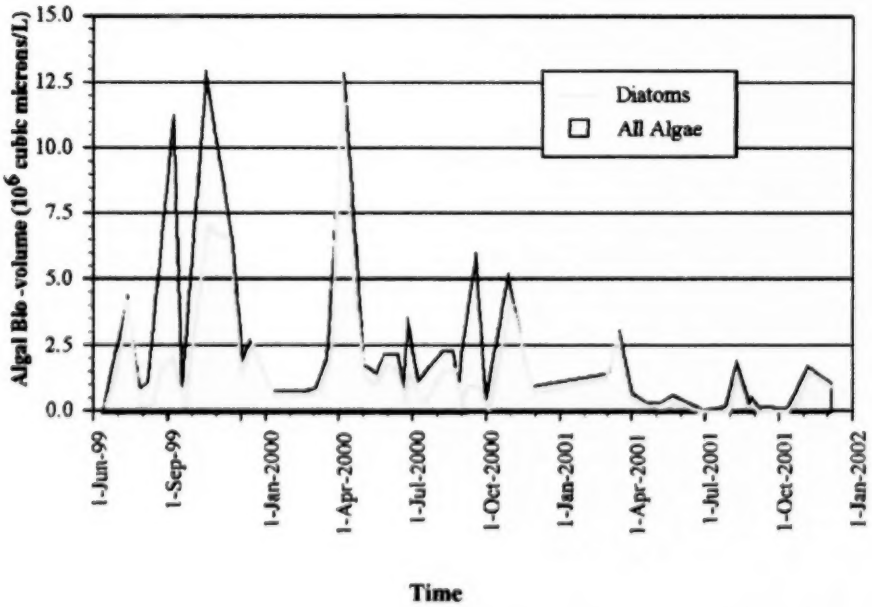

Figure 5. Comparison between the total algal bio-volume and the bio-volume of diatoms (Class Bacillariophyceae) in samples collected from the Assiniboine River at the Portage la Prairie WTP from June1999 to December 2001.

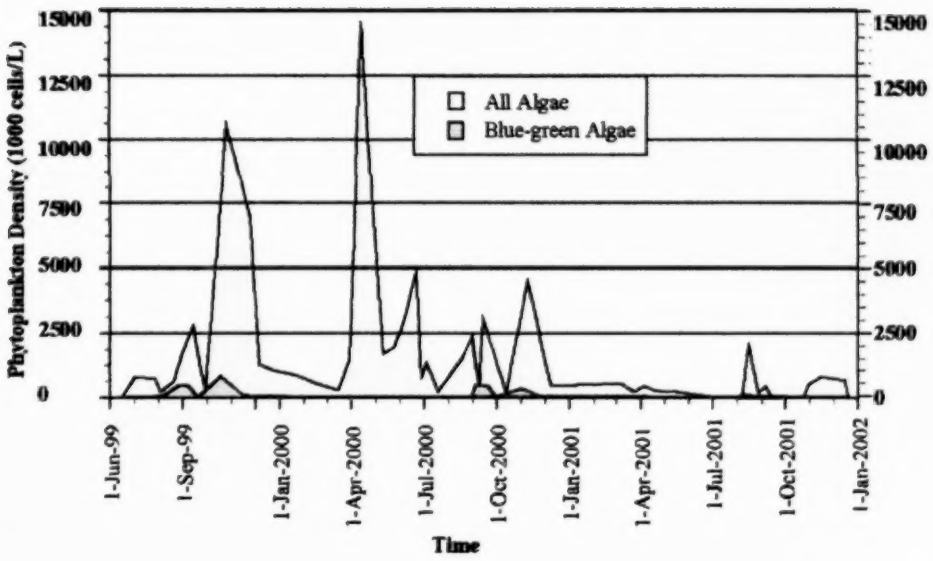

Figure 6. Comparison between the total algal density and the density of blue-green algae (Class Myxophyceae) in samples collected from the Assiniboine River at the Portage la Prairie WTP from June1999 to December 2001.

Relationships Between Variables

Chlorophyll-*a* content was only weakly correlated with total phytoplankton density (r = 0.44) and bio-volume (r = 0.41) over the period of record. The peak in phytoplankton growth in the fall of 1999 was accompanied by a rise in chlorophyll-*a*, as was the peak in phytoplankton growth during the spring of 2000 (Figure 7). However, there were also numerous sample dates when chlorophyll-*a* levels were high and the density and bio-volume of phytoplankton were low (and vice versa). One would have expected a relatively strong positive relationship between chlorophyll-*a* and phytoplankton population growth. Why this was not the case is not known. Most of the phytoplankton consisted of diatoms and green algae species, and since these species do not produce microcystin-LR there was no significant correlation between toxin levels and the total phytoplankton population data or the chlorophyll-*a* content data (Figure 7). Statistical analysis showed that there was no correlation between levels of the toxin and blue-green algae density (r=-0.002) (see Figure 8) or blue-green algae bio-volume (r=-0.003). This indicated that blue-green algae population data could not be used to reliably predict toxin concentrations at this site.

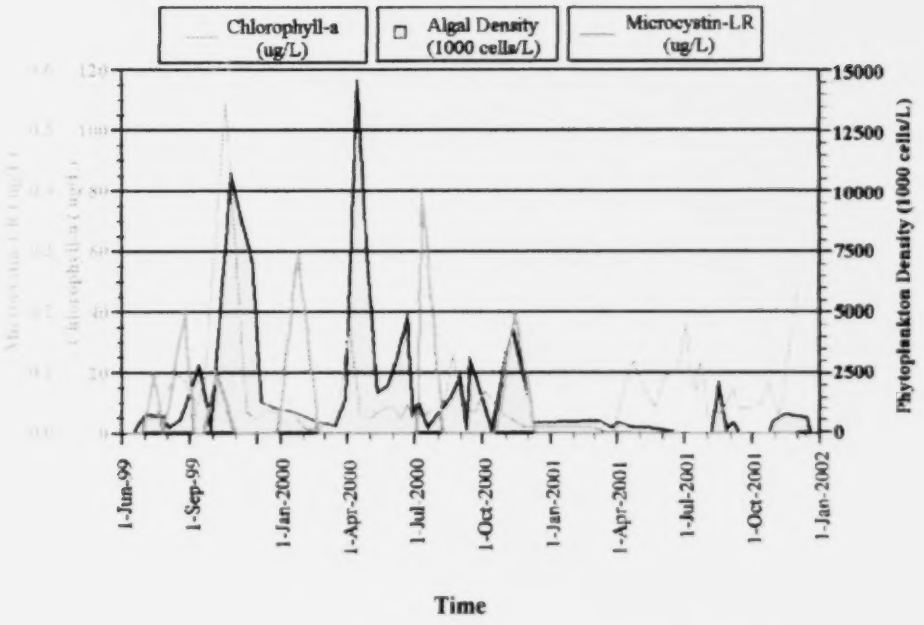

Figure 7. Microcystin-LR concentrations, chlorophyll-*a* content, and phytoplankton densities in raw water samples collected from the Assiniboine River at the Portage la Prairie WTP from June 1999 to December 2001.

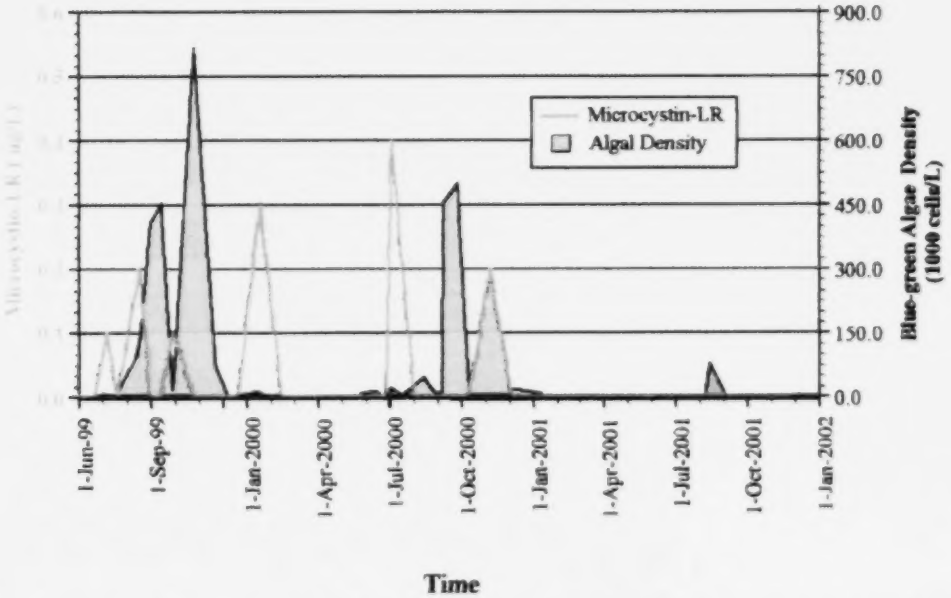

Figure 8. Microcystin-LR concentrations and blue-green algae densities in raw water samples collected from the Assiniboine River at the Portage la Prairie WTP from June 1999 to December 2001.

CONCLUSIONS

A number of general conclusions can be made based on the results of the monitoring program:

1. Microcystin-LR was detected in about 1/3 of the raw water samples and none of the treated water samples collected from the WTP over the period of monitoring from 1997 through 2001.

2. The treatment process used at the WTP appeared to be successful at removing the toxin. However, toxin levels in the raw water supply were generally quite low during the monitoring period.

3. The highest level of toxin recorded was 0.7 ug/L, which is well below the proposed drinking water guideline of 1.5 ug/L.

4. Concentrations of microcystin-LR varied over the course of the program, but tended to be highest during the late summer and fall periods.

5. *Aphanizomenon flos-aquae* dominated the blue-green algae component of the micro-flora, and as such, may have been primarily responsible for the majority of the toxin production at the site.

6. The river supports a diverse, species rich, and at times highly dense, population of phytoplankton. However, blue-green algae species accounted for only a small portion of the total phytoplankton population at the site.

7. No clear relationship existed between toxin concentrations and chlorophyll-*a* content and phytoplankton population data. As such, it was not possible to accurately predict toxin production based on phytoplankton population statistics and chlorophyll-*a* content.

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APPENDIX

Table A1. Results from monitoring of microcystin-LR (MLR) and chlorophyll-*a* at the Portage la Prairie WTP since May 1997 – December 2001 (n/a = not analyzed).

Date Sampled	MLR (ug/L) Raw Water	MLR (ug/L) Treated Water	Chlorophyll-*a* (ug/L) Raw Water
15-May-97	0.5	<0.1	n/a
13-Jun-97	<0.1	n/a	n/a
11-Jul-97	<0.1	n/a	n/a
08-Aug-97	<0.1	n/a	n/a
14-Aug-97	0.1	n/a	n/a
04-Sep-97	<0.1	n/a	n/a
25-Sep-97	<0.1	<0.1	n/a
03-Oct-97	<0.1	n/a	n/a
31-Oct-97	0.2	<0.1	n/a
28-Nov-97	<0.1	n/a	n/a
30-Apr-98	<0.1	n/a	n/a
07-May-98	<0.1	n/a	n/a
14-May-98	<0.1	n/a	n/a
21-May-98	<0.1	n/a	n/a
28-May-98	<0.1	n/a	n/a
04-Jun-98	<0.1	n/a	n/a
11-Jun-98	<0.1	n/a	n/a
18-Jun-98	0.1	n/a	n/a
25-Jun-98	<0.1	n/a	n/a
02-Jul-98	<0.1	n/a	n/a
09-Jul-98	0.1	n/a	n/a
16-Jul-98	0.1	n/a	n/a
24-Jul-98	0.1	n/a	n/a
30-Jul-98	0.1	n/a	n/a
06-Aug-98	0.6	<0.1	n/a
13-Aug-98	0.7	<0.1	n/a
20-Aug-98	0.3	<0.1	n/a
27-Aug-98	0.2	<0.1	n/a
03-Sep-98	<0.1	n/a	n/a
10-Sep-98	<0.1	n/a	n/a
17-Sep-98	0.2	n/a	n/a
24-Sep-98	0.2	n/a	n/a
01-Oct-98	0.2	n/a	n/a
08-Oct-98	0.2	n/a	n/a
15-Oct-98	0.1	n/a	n/a
22-Oct-98	0.2	n/a	n/a
29-Oct-98	0.1	n/a	n/a
05-Nov-98	0.1	n/a	n/a
12-Nov-98	<0.1	n/a	n/a
19-Nov-98	0.1	n/a	n/a

Table A1 (continued)

Date Sampled	MLR (ug/L) Raw Water	MLR (ug/L) Treated Water	Chlorophyll-*a* (ug/L) Raw Water
26-Nov-98	0.2	n/a	n/a
03-Dec-98	0.1	n/a	n/a
11-Dec-98	0.2	n/a	n/a
18-Dec-98	0.3	n/a	n/a
24-Dec-98	0.1	n/a	n/a
31-Dec-98	0.2	n/a	n/a
07-Jan-99	0.1	n/a	n/a
14-Jan-99	<0.1	n/a	n/a
21-Jan-99	<0.1	n/a	n/a
28-Jan-99	<0.1	n/a	n/a
04-Feb-99	<0.1	n/a	n/a
11-Feb-99	0.1	n/a	n/a
01-Jun-99	<0.1	n/a	5
15-Jun-99	<0.1	n/a	1
29-Jun-99	0.1	n/a	5
13-Jul-99	<0.1	n/a	5
27-Jul-99	0.1	n/a	12
10-Aug-99	0.2	n/a	20
24-Aug-99	<0.1	n/a	18
07-Sep-99	<0.1	n/a	6
21-Sep-99	0.1	n/a	19
19-Oct-99	<0.1	n/a	110
16-Nov-99	<0.1	n/a	7
30-Nov-99	<0.1	n/a	5
14-Dec-99	<0.1	n/a	8
11-Jan-00	0.3	<0.1	8
08-Feb-00	<0.1	n/a	1
07-Mar-00	<0.1	n/a	4
21-Mar-00	<0.1	n/a	12
04-Apr-00	<0.1	n/a	35
18-Apr-00	<0.3	n/a	6
01-May-00	<0.3	n/a	5
16-May-00	<0.2	n/a	8
30-May-00	<0.2	n/a	9
13-Jun-00	<0.2	n/a	5
20-Jun-00	<0.2	n/a	10
27-Jun-00	0.4	<0.2	6
11-Jul-00	0.2	n/a	6
26-Jul-00	<0.2	n/a	8
08-Aug-00	<0.2	n/a	10

Table A1 (continued)

Date Sampled	MLR (ug/L) Raw Water	MLR (ug/L) Treated Water	Chlorophyll-*a* (ug/L) Raw Water
22-Aug-00	<0.2	n/a	26
05-Sep-00	<0.2	n/a	8
19-Sep-00	<0.2	n/a	7
03-Oct-00	<0.2	n/a	14
31-Oct-00	0.2	n/a	6
28-Nov-00	<0.2	n/a	2
30-Jan-01	<0.2	n/a	2
27-Feb-01	<0.2	n/a	2
13-Mar-01	<0.2	n/a	1
27-Mar-01	<0.2	n/a	<1
10-Apr-01	<0.2	n/a	15.4
24-Apr-01	<0.2	n/a	24.2
08-May-01	<0.2	n/a	13.8
22-May-01	<0.2	n/a	8.8
05-Jun-01	<0.2	n/a	19.4
19-Jun-01	<0.2	n/a	20
26-Jun-01	<0.2	n/a	25.7
03-Jul-01	<0.2	n/a	36.9
10-Jul-01	<0.2	n/a	19.7
17-Jul-01	<0.2	n/a	13.9
24-Jul-01	<0.2	n/a	24.5
31-Jul-01	<0.2	n/a	6.5
07-Aug-01	<0.2	n/a	5.2
14-Aug-01	<0.2	n/a	6.9
21-Aug-01	<0.2	n/a	7
28-Aug-01	<0.2	n/a	11.1
05-Sep-01	<0.2	n/a	15.1
11-Sep-01	<0.2	n/a	8.1
25-Sep-01	<0.2	n/a	8.3
10-Oct-01	<0.2	n/a	9.7
23-Oct-01	<0.2	n/a	16.4
06-Nov-01	<0.2	n/a	5.8
04-Dec-01	<0.2	n/a	50.5

Table A2. Summary of algal cell densities (x 1000 cells/L) for each phytoplankton class in samples collected from June 1999 – December 2001.

Sample Date	Bacillariophyceae	Chlorophyceae	Chrysophyceae	Cryptophyceae	Euglenophyceae	Myxophyceae	Peridineae	Total Density
15-Jun-99	24	3		24				51
29-Jun-99	348	88		77	6	4		523
12-Jul-99	374	55		29	2	3		463
27-Jul-99	105	34		14		47		200
10-Aug-99	294	97		33	3	124		551
24-Aug-99	1.040	41	2	278	10	410	4	1.785
7-Sep-99	1.894	319		86	1	459	7	2.766
21-Sep-99	48	12		19	2	6		87
19-Oct-99	8.608	846		114	65	831		10.464
16-Nov-99	6.523	210		49		84		6.866
30-Nov-99	970	183		15		7		1.175
14-Dec-99	854	177	1	11	3	6	2	1.054
11-Jan-00	437	91		279	1	14		822
8-Feb-00	259	61		47				367
7-Mar-00	132	77	2	14	4	33	8	270
21-Mar-00	1.315	139	2	18	7		2	1.483
4-Apr-00	14.316	67	23	18	43		6	14.473
18-Apr-00	6.813	351	20	3	12	5	10	7.214
1-May-00	1.277	224	164	5	35	4	2	1.711
16-May-00	932	842	37	3	32	2		1.848
30-May-00	2.283	692		12	7	15		3.009
13-Jun-00	3.303	1.567	15		2	11		4.898
20-Jun-00	198	451		42	2	1		694
27-Jun-00	686	485	1		4	24		1.200
11-Jul-00	179	34		20	18	2		253
8-Aug-00	1.338	117		40	4	46		1.545
22-Aug-00	1.710	525		37	3	6		2.281
31-Aug-00	163	63	3	7	5	7		248
5-Sep-00	1.641	908	10	62	5	449		3.075
19-Sep-00	889	227		34		500		1.650
3-Oct-00	37	17		3	5	25		87
31-Oct-00	3.835	162		163	10	304		4.474
28-Nov-00	227	83		31	2	16		359
30-Jan-01	516	7		11	1	1		536
27-Feb-01	430	9	3	34		3		479
13-Mar-01	244			21	2	2		269
27-Mar-01	280	38		15		2		335
10-Apr-01	160			46		1		207
24-Apr-01	181	4		68				253
8-May-01	125	37	3	99	2			266
22-May-01	62	3	7	52	2			126
26-Jun-01	3	3		0		1		7
3-Jul-01	4	6						10
17-Jul-01	5	2		2				9
24-Jul-01	8	3		1	0		0	12
31-Jul-01	4	4		1		5		14
8-Aug-01	1.566	19		293		82		1.960
21-Aug-01	64	44		36				144
28-Aug-01	141	7	7	61	7	5		228
5-Sep-01	3	1	1		1	1		7
11-Sep-01	2	0	0	1	0	0		4
25-Sep-01	6	1	1	0	0	1		8
10-Oct-01	0							0
23-Oct-01	292	64		43		111		510
6-Nov-01	655	30	4	21				710
4-Dec-01	478	65		54		48		645

Table A3. Summary of algal cell bio-volume data (x 1000 μ^3) for each phytoplankton class in samples collected from June 1999 – December 2001.

Date	Bacillariophyceae	Chlorophyceae	Chrysophyceae	Cryptophyceae	Euglenophyceae	Myxophyceae	Peridineae	Total Bio-volume
15-Jun-99	213.375	28.800		42.450				284.625
29-Jun-99	1,584.650	248.785		24.150	45.000	3.800		1,906.385
12-Jul-99	4,206.695	106.342		17.300	42.000	6.000		4,378.337
27-Jul-99	124.310	81.445		9.850		597.250		812.855
10-Aug-99	259.335	342.283		8.800	56.250	393.200		1,059.868
24-Aug-99	1,723.780	243.453	4.500	105.250	76.500	1,615.850	32.000	3,801.333
7-Sep-99	2,081.850	1,144.400		6.550	36.000	7,938.500	98.000	11,305.300
21-Sep-99	142.080	15.963		22.250	11.520	9.612		201.425
19-Oct-99	7,056.430	226.600		61.020	227.500	5,344.000		12,915.550
16-Nov-99	6,529.160	92.080		52.224		89.400		6,762.864
30-Nov-99	1,424.060	40.960		29.250		11.200		1,505.470
14-Dec-99	2,557.805	37.608	4.500	29.250	13.000	2.400	28.000	2,672.563
11-Jan-00	604.876	16.640		115.250	4.500	25.200		766.466
8-Feb-00	608.065	14.910		20.500				643.475
7-Mar-00	723.855	13.500	6.750	8.750	64.000	32.800	20.096	869.751
21-Mar-00	1,997.159	33.360	6.750	22.448	63.200		12.000	2,134.917
4-Apr-00	12,595.780	30.514	77.625	19.350	197.000		46.125	12,966.394
18-Apr-00	5,253.760	105.220	35.350	3.840	62.400	31.250	187.500	5,679.320
1-May-00	1,422.995	221.180	11.745	3.380	63.000	66.500	16.000	1,804.800
16-May-00	997.740	394.624	13.818	3.072	37.920	2.000		1,449.174
30-May-00	1,815.210	179.240		4.450	49.000	12.750		2,060.650
13-Jun-00	1,569.290	506.280	7.680		4.320	31.628		2,119.198
20-Jun-00	346.190	504.175		10.500	5.120	400		866.385
27-Jun-00	1,499.180	1,636.117	3.375		24.000	214.960		3,377.632
11-Jul-00	269.664	856.500		31.250	38.880	10.000		1,206.294
8-Aug-00	1,567.340	251.430		18.250	30.960	433.265		2,301.245
22-Aug-00	1,601.059	482.848		37.600	1.125	59.800		2,182.432
31-Aug-00	220.728	59.755	24.000	1.750	21.600	28.700		356.533
5-Sep-00	998.620	445.935	9.600	43.000	39.000	1,741.600		3,277.755
19-Sep-00	997.270	3,128.435		8.500		1,811.200		5,945.405
3-Oct-00	25.734	46.320		750	13.184	173.460		259.448
31-Oct-00	4,267.956	296.220		40.750	67.500	539.400		5,211.826
28-Nov-00	728.085	87.210		11.500	36.000	19.160		881.955
30-Jan-01	1,114.500	25.320		2.750	18.000	42.875		1,203.445
27-Feb-01	1,301.180	18.700	10.125	17.250		46.875		1,394.130
13-Mar-01	2,920.750			10.500	16.000	31.250		2,978.500
27-Mar-01	558.840	201.440		3.750		85.750		849.780
10-Apr-01	316.835			16.650		500		333.985
24-Apr-01	205.023	820		46.250				252.093
8-May-01	98.345	11.780	1.125	104.500	8.000			223.750
22-May-01	310.870	720	8.000	89.500	11.250			420.340
26-Jun-01	10.734	6.866		250		1.753		19.603
3-Jul-01	9.070	17.829						26.899
17-Jul-01	9.518	6.340		2.725				18.583
24-Jul-01	21.880	11.648		2.025	800		338	36.690
31-Jul-01	13.796	14.362		525		22.506		51.182
8-Aug-01	1,472.135	32.195		73.250		65.606		1,643.180
21-Aug-01	130.095	14.080		9.000				153.175
28-Aug-01	237.835	4.230	10.500	32.750	42.000	2.000		329.315
5-Sep-01	3.032	2.408	3.038		2.350	2.610		13.438
11-Sep-01	14.978	650	675	1.425	1.024	120		18.872
25-Sep-01	11.544	2.063	2.700	400	2.500	1.260		20.467
10-Oct-01	640							640
23-Oct-01	369.545	47.350		28.250		88.806		533.945
6-Nov-01	1,549.285	7.480	7.250	36.750				1,600.765
4-Dec-01	924.850	9.385		36.250		46.806		1,017.285

Table A4. Blue-green algae cell density and bio-volume data in samples collected from June 1999 – December 2001.

Sample Date	Species	Density (x 1000 cells/L)	Unit Biovolume (μ^3)	Total Biovolume (x 1000 μ^3)
29-Jun-99	*Aphanizomenon flos-aquae*	1	3,125	3,125
29-Jun-99	*Merismopedia* sp.	3	225	675
12-Jul-99	*Anabaena* sp.	2	1,500	3,000
12-Jul-99	*Aphanizomenon flos-aquae*	1	3,000	3,000
27-Jul-99	*Anabaena* sp.	11	1,200	13,200
27-Jul-99	*Aphanizomenon flos-aquae*	3	3,700	11,100
27-Jul-99	*Aphanocapsa* sp.	3	14,000	42,000
27-Jul-99	*Chroococcus* sp.	7	4,200	29,400
27-Jul-99	*Coelosphaerium* sp.	3	14,000	42,000
27-Jul-99	*Gomphosphaeria* sp.	2	14,000	28,000
27-Jul-99	*Merismopedia* sp.	5	510	2,550
27-Jul-99	*Microcystis aeruginosa*	13	33,000	429,000
10-Aug-99	*Anabaena* sp.	3	2,000	6,000
10-Aug-99	*Aphanizomenon flos-aquae*	121	3,200	387,200
24-Aug-99	*Anabaena* sp.	18	2,500	45,000
24-Aug-99	*Aphanizomenon flos-aquae*	363	3,200	1,161,600
24-Aug-99	*Gomphosphaeria* sp.	26	15,625	406,250
24-Aug-99	*Merismopedia punctata*	3	1,000	3,000
7-Sep-99	*Anabaena* sp.	13	1,200	15,600
7-Sep-99	*Aphanizomenon flos-aquae*	163	3,700	603,100
7-Sep-99	*Aphanocapsa* sp.	20	110,000	2,200,000
7-Sep-99	*Gomphosphaeria* sp.	51	14,000	714,000
7-Sep-99	*Merismopedia* sp.	46	800	36,800
7-Sep-99	*Merismopedia tenuissima*	95	400	38,000
7-Sep-99	*Microcystis aeruginosa*	16	270,000	4,320,000
7-Sep-99	*Planktolyngbya* sp.	55	200	11,000
21-Sep-99	*Aphanizomenon flos-aquae*	3	2,500	7,500
21-Sep-99	*Lyngbya limnetica*	1	600	600
21-Sep-99	*Merismopedia punctata*	1	512	512
21-Sep-99	*Spirulina* sp.	1	1,000	1,000
19-Oct-99	*Aphanizomenon flos-aquae*	815	6,400	5,216,000
19-Oct-99	*Aphanocapsa delicatissima*	16	8,000	128,000
16-Nov-99	*Gomphosphaeria* sp.	1	64,000	64,000
16-Nov-99	*Planktolyngbya* sp.	82	300	24,600
16-Nov-99	*Pseudoanabaena* sp.	1	800	800
30-Nov-99	*Aphanizomenon flos-aquae*	3	3,200	9,600
30-Nov-99	*Pseudoanabaena* sp.	4	400	1,600
14-Dec-99	*Planktolyngbya* sp.	4	400	1,600
14-Dec-99	*Pseudoanabaena* sp.	2	400	800
11-Jan-00	*Aphanizomenon flos-aquae*	3	4,000	12,000
11-Jan-00	*Gomphosphaeria* sp.	1	10,000	10,000
11-Jan-00	*Lyngbya limnetica*	10	320	3,200
7-Mar-00	*Aphanizomenon flos-aquae*	2	4,000	8,000
7-Mar-00	*Lyngbya limnetica*	31	800	24,800
18-Apr-00	*Aphanizomenon flos-aquae*	5	6,250	31,250
1-May-00	*Aphanizomenon flos-aquae*	2	6,250	12,500
1-May-00	*Gomphosphaeria* sp.	2	27,000	54,000
16-May-00	*Anabaena* sp.	2	1,000	2,000
3· May-00	*Gomphosphaeria* sp.	2	3,375	6,750
30-May-00	*Lyngbya* sp.	2	800	1,600
30-May-00	*Merismopedia sp.*	11	400	4,400
13-Jun-00	*Anabaena* sp.	1	7,500	7,500
13-Jun-00	*Aphanizomenon flos-aquae*	1	2,400	2,400
13-Jun-00	*Lyngbya* sp.	5	800	4,000
13-Jun-00	*Merismopedia sp.*	2	864	1,728
13-Jun-00	*Microcystis* sp.	2	8,000	16,000

Table A4. Blue-green algae cell density and bio-volume data (continued).

Sample Date	Species	Density (x 1000 cells/L)	Unit Biovolume (μ^3)	Total Biovolume (x 1000 μ^3)
20-Jun-00	*Lyngbya* sp.	1	400	400
27-Jun-00	*Anabaena* sp.	20	7,500	150,000
27-Jun-00	*Chroococcus* sp.	1	64,000	64,000
27-Jun-00	*Lyngbya* sp.	3	320	960
11-Jul-00	*Aphanizomenon flos-aquae*	2	5,000	10,000
8-Aug-00	*Aphanizomenon flos-aquae*	1	6,250	6,250
8-Aug-00	*Gomphosphaeria* sp.	3	15,625	46,875
8-Aug-00	*Lyngbya* sp.	2	320	640
8-Aug-00	*Merismopedia* sp.	39	500	19,500
8-Aug-00	*Microcystis* sp.	1	360,000	360,000
22-Aug-00	*Aphanizomenon flos-aquae*	2	2,500	5,000
22-Aug-00	*Gomphosphaeria* sp.	2	27,000	54,000
22-Aug-00	*Lyngbya* sp.	2	400	800
31-Aug-00	*Aphanizomenon flos-aquae*	2	5,000	10,000
31-Aug-00	*Gomphosphaeria* sp.	2	8,000	16,000
31-Aug-00	*Merismopedia* sp.	3	900	2,700
5-Sep-00	*Anabaena* sp.	55	2,000	110,000
5-Sep-00	*Aphanizomenon flos-aquae*	287	5,000	1,435,000
5-Sep-00	*Gomphosphaeria* sp.	1	8,000	8,000
5-Sep-00	*Lyngbya* sp.	103	1,200	123,600
5-Sep-00	*Merismopedia* sp.	2	500	1,000
5-Sep-00	*Microcystis* sp.	1	64,000	64,000
19-Sep-00	*Anabaena* sp.	10	2,000	20,000
19-Sep-00	*Aphanizomenon flos-aquae*	316	5,000	1,580,000
19-Sep-00	*Gomphosphaeria* sp.	3	2,000	6,000
19-Sep-00	*Lyngbya* sp.	171	1,200	205,200
3-Oct-00	*Aphanizomenon flos-aquae*	23	7,500	172,500
3-Oct-00	*Lyngbya* sp.	2	480	960
31-Oct-00	*Aphanizomenon flos-aquae*	33	5,000	165,000
31-Oct-00	*Gomphosphaeria* sp.	10	27,000	270,000
31-Oct-00	*Lyngbya* sp.	261	400	104,400
28-Nov-00	*Gomphosphaeria* sp.	3	5,000	15,000
28-Nov-00	*Lyngbya* sp.	13	320	4,160
30-Jan-01	*Gomphosphaeria* sp.	1	42,875	42,875
27-Feb-01	*Gomphosphaeria* sp.	3	15,625	46,875
13-Mar-01	*Gomphosphaeria* sp.	2	15,625	31,250
27-Mar-01	*Gomphosphaeria* sp.	2	42,875	85,750
24-Apr-01	*Aphanizomenon flos-aquae*	1	500	500
3-Jul-01	*Lyngbya* sp.	0.2	800	160
3-Jul-01	*Merismopedia* sp.	0.2	150	30
3-Jul-01	*Microcystis* sp.	0.1	15625	1562.5
31-Jul-01	*Anabaena* sp.	0.6	2500	1500
31-Jul-01	*Aphanizomenon flos-aquae*	4.2	5000	21000
8-Aug-01	*Lyngbya* sp.	82	800	65,600
28-Aug-01	*Merismopedia* sp.	5	400	2,000
5-Sep-01	*Aphanizomenon flos-aquae*	0.5	5,000	2,500
5-Sep-01	*Lyngbya* sp.	0.1	800	80
5-Sep-01	*Merismopedia punctata*	0.2	150	30
11-Sep-01	*Merismopedia punctata*	0.1	1,200	120
25-Sep-01	*Aphanizomenon flos-aquae*	0.2	4,800	960
25-Sep-01	*Lyngbya* sp.	0.3	800	240
25-Sep-01	*Merismopedia punctata*	0.1	600	60
23-Oct-01	*Lyngbya* sp.	111	800	88,800
4-Dec-01	*Aphanizomenon flos-aquae*	2	5,000	10,000
4-Dec-01	*Lyngbya* sp.	46	800	36,800